

ENHANCEMENTS TO THE CROSS CORRELATION TECHNIQUE FOR EXTRAPOLATING GEOSTATIONARY SATELLITE IMAGERY

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27 November 1996

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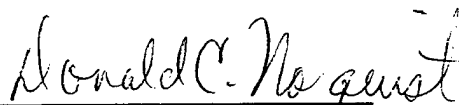
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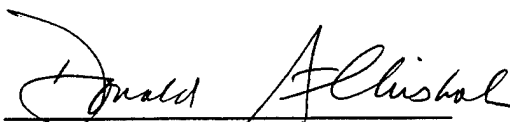


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| 13. ABSTRACT (Maximum 200 words) This report documents enhancements made to the cross correlation technique for extrapolating geostationary satellite imagery up to five hours into the future. Because it requires only two geostationary images to utilize the technique, it satisfies an important Air Force requirement to be able to forecast the distribution of cloud in data restricted environments. The enhancements referred to above include techniques to prevent "terrain advection," reduce border contamination, and to minimize excessive smoothing of cloud features. In addition, an interactive Graphic User Interface has been developed to facilitate use of the technique by operational weather forecasters. | | | | |
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Enhancements to the Cross Correlation Technique for Extrapolating Geostationary Satellite Imagery

1. INTRODUCTION

Accurate nowcasting (0-2 hours) and very short-range forecasting (up to 6 hours) of cloud features has long been a top priority of the Air Force. Knowledge of the distribution of cloud is essential for communication, training exercises, tactical deployment of military aircraft, and surveillance. Such forecasts must often be made with a minimum of observational data to accommodate tactical situations in which observations are largely unavailable or detection must be prevented.

Since 1989, developing, evaluating, and refining methods for data-sparse forecasting has been an important component of the research conducted within the Atmospheric Sciences Division of Phillips Laboratory (PL/GPA). Early efforts focused on identification, isolation, and extrapolation of individual cloud features based on infrared brightness temperature contours. Heideman et al (1990), Ruggiero and Heideman (1992), and Nehrkorn et al (1993) have documented the details and evaluation of several contour extrapolation techniques.

In general, published results suggest that, with respect to simple persistence, some success in forecasting the shape, movement, and evolution of cloud features

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was achieved using contour extrapolation, but the disadvantages were significant. For example, none of the techniques studied were designed to account for the natural tendency of individual cloud features to split and merge with other clouds over time. Moreover, Heideman et al (1990) detail the cumbersome, largely manual, user-intensive contour selection process required to process an image and produce a forecast. The computational and manual expense precluded researchers from evaluating a sufficient number of contour extrapolation cases to make a definitive recommendation to either expand research on the use of one or more of the candidate techniques, or to move in a different research direction.

As a result, in 1992 PL initiated a project to test the established candidate contour extrapolation techniques, as well as to investigate other possible techniques, pursuant to declaring one technique most suitable for further development and potential operational implementation. Detailed findings are documented by Nehrkorn et al (1993). A whole-image extrapolation technique was developed in the comparisons study. This method was based on the statistical technique of cross correlation. It was demonstrably superior to the candidate contour extrapolation techniques as well as to persistence. The technique required only two consecutive geostationary visible or infrared satellite images, 30 or 60 minutes apart, to produce forecast images up to 5 hours into the future. This means that the technique can be used in data-restricted circumstances.

Infrared imagery has been used exclusively in this study to take advantage of its 24-hour utility. For display purposes, pixel infrared brightness temperatures are routinely converted to grayshade units using a linear scale. Forecasts were the product of displacement vectors based on differences in pixel position and brightness between the two observed images needed to initiate the technique.

Beyond better verification scores, cross correlation had a two-fold advantage over the other techniques considered. First, it implicitly accounted for splitting and merging cloud features. Second, forecast products could be looped like a series of actual geostationary images. For specific details of how the cross correlation technique works, and how geostationary imagery must be preprocessed prior to running the program, see Hamill and Nehrkorn (1992) and Nehrkorn et al (1993).

Cross correlation was selected as the cloud extrapolation technique with the greatest potential for further development and eventual operational implementation. However, there were obvious limitations of and problems with the cross correlation technique. For example, in largely clear scenes, terrain features such as lakes and rivers were often interpreted as cloud because their infrared brightness temperatures were significantly different from their surroundings. As a result, they would often be "advected" downstream in forecast satellite images. This came to be known as the "terrain advection" problem. In addition, contamination at the edges of the forecast images often became a problem. Finally, the technique was unable to represent or infer cloud

development or dissipation. These are among the major concerns that have been addressed in this report. We will also discuss an effort to develop an operational user interface for the cross correlation technique.

2. ENHANCEMENTS TO THE CROSS CORRELATION TECHNIQUE

Nehrkorn et al (1993) recommended that future work on the cross correlation technique be focused on addressing several key issues: terrain advection, border contamination, the loss of image contrast with time, and the lack of cloud development and dissipation. The following sections describe recent efforts to solve these problems.

2.1 Terrain Advection

As Hamill and Nehrkorn (1992) explain, the cross correlation technique employs a backwards trajectory scheme, whereby pixel intensities upstream (that is, at the origin of displacement vectors) become the forecast pixel intensity values. Problems arise when the upstream pixels are over bodies of water, which often have brightness signatures substantially different than the surrounding terrain. In these situations, oceans, lakes, and rivers are often interpreted as cloud, and the result is that they are advected downstream in the forecast imagery. Clearly, it is untenable to forecast that Lake Michigan, for example, will move to the east within a five-hour period.

The solution, as proposed by Hamill and Nehrkorn, is to use a nephanalysis valid at the time of the most recent observed satellite image. This nephanalysis provides information on which pixels were cloudy and which were clear. Because that image is the one from which all forecast images are generated, a check can be made for each pixel to determine whether its upstream counterpart was deemed clear or cloudy in the nephanalysis. To avoid terrain advection, upstream clear pixel intensities are simply not advected to the forecast pixel location; rather, a clearscene climatology pixel intensity value becomes the forecast value. This works well in theory, but it depends, of course, on the availability of a nephanalysis and representative clearscene mask for the study area. Moreover, the quality of the forecast images is obviously dependent on the accuracy of the nephanalysis. The availability of accurate nephanalysed data has benefitted from the Support of Environmental Requirements for Cloud Analysis and Archive (SERCAA) cloud analysis products (Isaacs, 1993 and Neu et al., 1994). Most of the geostationary imagery used in this project was made available through the SERCAA database at PL. One consequence of this has been the 60-minute interval between images archived for SERCAA, as compared to the half-hourly images used by Hamill and Nehrkorn (1992). As expected, the forecasts produced with the hourly images generally have larger RMSEs than the half-hourly images, but the difference is small through 2 hours (roughly 3%, on average). No direct comparative data exist

beyond 2 hours, as forecasts made using the half-hourly images were limited to 2.5 hours, as opposed to 5 hours using hourly images.

The primary task in Phase I of SERCAA, already completed, was to integrate multispectral imagery from geostationary and polar orbiting satellite platforms. Algorithms were applied to images from each individual platform and then to the integrated images to determine the distribution of cloud, both in a binary (0 = no cloud, 1 = cloud present) sense (on a pixel by pixel basis), and in terms of cloud fraction on a 1/16th-mesh basis (25km resolution).

The binary pixel by pixel analyses have been used in this project to prevent terrain advection. SERCAA nephanalyses were generated hourly over 10-day periods throughout 1992 and 1993 in several regions of interest (ROIs). The Eastern Mediterranean and Eastern Asian ROIs were used in evaluating and refining the cross correlation technique, and the Central American ROI was used in subsequent testing and evaluation (see Figure 1).

The clearscene climatology consists of a single image for each hour (Figure 2). It was created by identifying the minimum pixel intensity values on an hourly basis over the 10-day period composing each data set, and assigning that grayshade to that particular location in the clearscene. This is not an ideal solution, as by definition the clearscene pixels represent the low-end extreme grayshade values for a given hour and location over a 10-day period, and these pixels will often appear artificially darker than the corresponding verification satellite imagery. In tropical areas (for example, the eastern Asia ROI), cloud is often ubiquitous, and the minimum grayshade for a given hour over the 10-day period actually represents cloud for a number of pixels. This results in a slightly "milky" appearance of the clearscene image (see Figure 3). A possible solution for this is to set a maximum threshold for grayshade on the clearscene image that is less than the value likely to be associated with cloud in the area of interest.

Alternatively, it is possible to substitute color-coded pixels based on geography (land, coastline, water) for clearscene pixel values, using a 1/16th mesh resolution hemispheric database developed at PL for use in SERCAA. This "geography option" is currently being coded and will be explored as a viable operational alternative to the clearscene mask. The clearscene problem notwithstanding, the basic approach of not advecting upstream clear pixels is an unqualified success in preventing terrain advection. Testing of the technique over the eastern Mediterranean ROI, which contains portions of the Mediterranean and Red Seas, and Lake Nasser (easily distinguishable large bodies of water prone to spurious advection if a nephanalysis is not used), confirms that the approach of preventing advection of upstream clear pixels effectively eliminates the problem. The added

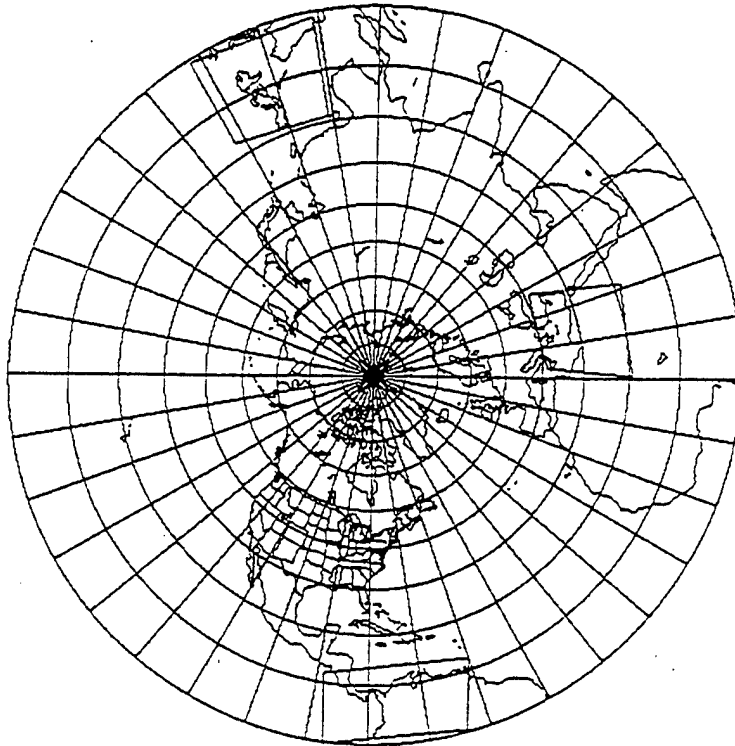


Figure 1: Cross Correlation technique Regions of Interest: Eastern Asia, Eastern Mediterranean, and Central and Northern South America.

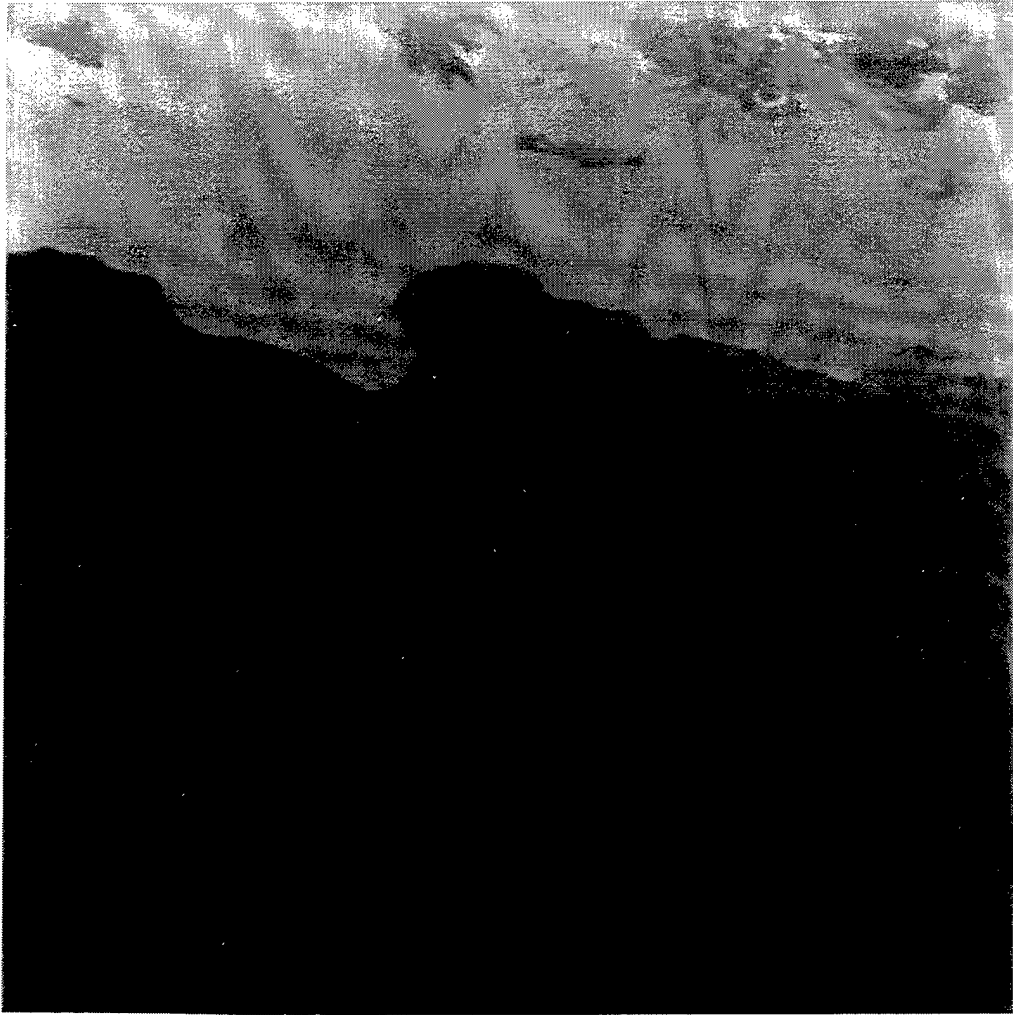


Figure 2: Example of hourly clearscene image for Eastern Mediterranean ROI.

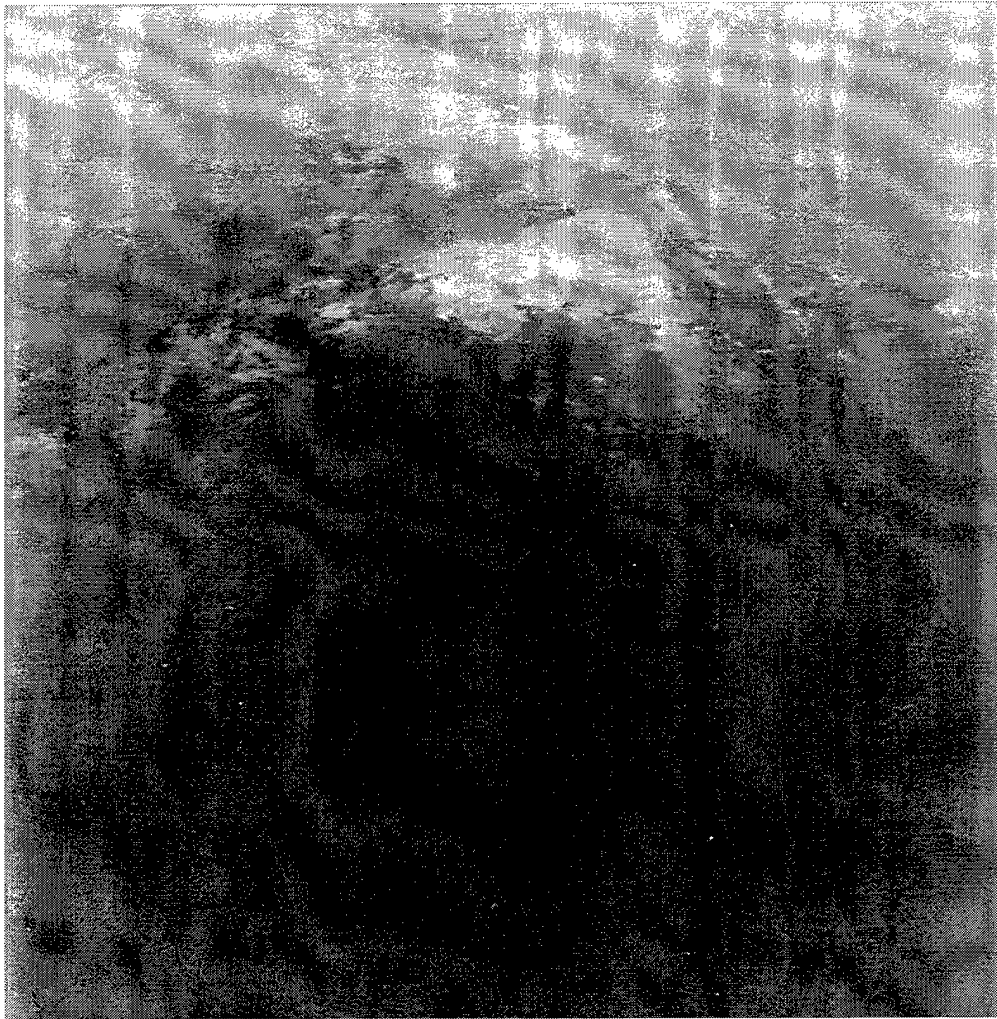


Figure 3: Example of hourly clearscene image for Eastern Asia ROI. Note cloud in upper portion of imager, indicating that, for this particular hour, a number of pixels were never actually clear throughout the available ten-day climatological sample of geostationary images.

computational cost is negligible when compared to the benefit of ensuring an anchored background under moving clouds in forecast animation loops.

2.2 Border Contamination

Inaccuracies and distortions along the boundary of any limited-area domain are to be expected. Advection of pixel gray shade values based on a recent history of their positions is the essence of the cross correlation technique. There is no such information outside the image domain, and advection right at the boundary is zero. Often, the result is distorted cloud features at the edge of the domain that appear blurred and/or fail to move in synch with the rest of the forecast images when looped. Cloud features that existed just outside the image domain at the time of the latest observed image cannot be incorporated in forecast images.

Our solution to the border contamination problem was to enlarge the domain over which the technique was applied but to display only the inner domain of the original size. Prior to addressing this problem, we had uniformly worked with 256 x 256 pixel infrared images, with resolutions varying between 4 km for METEOSAT (Europe and environs) and GMS (greater Asia), and 8-km for GOES-7 (Americas). The question of how large the additional buffer should be was important, as the computational expense of increasing the image domain was non-trivial. The primary consideration was that it be large enough that contamination at the edge of the buffer domain in the first forecast image not advect into the inner domain during the 5-hour forecast period. Assuming an average advective speed of 80 km/hr and basing our calculations on the best available resolution of 4 km, we calculated a displacement of 100 pixels (400 km) in 5 hours. That was the minimum desired width of the buffer zone. We conservatively settled on a buffer zone 128 pixels wide to add to the original 256 x 256. As a result, the working domain became 384 x 384 pixels, thus providing a buffer of 64 pixels on each side of the displayed 256 x 256 image.

Testing suggested that the approach is very effective, with whole-image root mean square errors (RMSE) reduced an average of 15-20 percent; the subjective aesthetic improvement seemed far greater. The best improvement was for those images with a great deal of cloud along the edge or just outside of the observed 256 x 256 images.

The cost of the improvement, however, has been a 20-25 percent increase in computer time, bringing the run time to nearly 25 minutes on a VAX4000 workstation for a 5-hour forecast. Reducing the width of the buffer would certainly help in this regard, but the resulting increased probability that distorted cloud would find its way into the later forecast images makes that a questionable strategy. A better solution would be to optimize the code to speed up execution of the program (see Section 3a) and to use a more powerful computer to execute the cross correlation technique.

2.3 Excessive Smoothing of Cloud Features

Of the four basic problems with the cross correlation technique mentioned at the beginning of this section, we feel that the slight loss of contrast over time in the forecast images is the least serious. However, it was certainly worth solving in our attempt to produce the most realistic looking forecast images possible.

The smoothing problem results from excessive smoothing and averaging in the extrapolation process. The key to remedying it lies in determining at what points in the process of generating the forecast images, if any, averaging is unnecessary and can be eliminated without adversely affecting the end product. Averaging is required in calculating the cross correlation displacement vector field, running the quality control filter, and performing the objective analysis to assign displacement vectors at every pixel (Hamill and Nehrkorn, 1992). However, there was some flexibility in two other components of the program that applied varying degrees of smoothing and averaging to the forecast satellite images: the use of bilinear interpolation to produce forecast grayshade values and the number of times it is used when tracing a grayshade back to its original location (a necessary step in determining the value of the pixel in the next forecast frame).

When using the backwards trajectory scheme described in Hamill and Nehrkorn (1992) to obtain forecast grayshade values, displacement vectors are followed back to their origin in an earlier frame, which may or may not lie directly on a pixel. Bilinear interpolation, which is a weighted average of the surrounding four pixel values, has been used to compute the forecast pixel value in such cases. This is certainly a reasonable approach, but may result in a subtle smoothing of cloud features on forecast imagery that increases with increasing forecast interval. As Hamill and Nehrkorn point out, one alternative would be to round the trajectory calculation to the nearest pixel instead of using bilinear interpolation; this would result in sharper images, but likely at the expense of accuracy.

To test this notion, eight cross correlation cases were run with and without bilinear interpolation, using 30 and 60 minute intervals between observed images. RMSEs were computed separately for each of the five forecast images and each of these were averaged over the eight cases. Results are shown in Table 1. It is apparent that use of bilinear interpolation reduced RMSE regardless of the time interval between images and at all forecast times, on average, by as much as 12.3 percent for a 2.5-hour forecast for the 30-minute update images, and by as much as 16.1 percent for a 5-hour forecast using the hourly updated images. A reduction in whole-image RMSE does not always reflect an improvement in the subjective visual quality of the forecast images. Indeed, in these cases, elimination of bilinear interpolation did not produce dramatically sharper images. Nevertheless, the decision was made on the basis of objective and subjective testing to retain bilinear interpolation in the cross correlation code.

The question of how many *times* to apply bilinear interpolation in producing a forecast image remained. The cross correlation technique was originally configured iteratively, such that a forecast for hour H was based on the previous hour's (H minus 1) forecast image, which had in turn been based on the forecast at H minus 2, and so on, resulting in forecast grayshade values that had been bilinearly interpolated several times. Alternatively, in an effort to minimize smoothing, we have attempted to trace *all* grayshade trajectories (displacement vectors) back to their origins in the most recent *observed* image, regardless of the forecast interval involved. This has produced uniformly sharper-looking forecast images without sacrificing accuracy (as measured by RMSE). We therefore recommend the non-iterative approach to the smoothing problem.

2.4 Development and Dissipation of Cloud

The cross correlation technique is best suited to producing forecast satellite imagery in the cool season (October - March in the Northern Hemisphere) over midlatitude areas. This is because the original technique was designed only to advect existing cloud, and advective processes often dominate in extratropical regions from late autumn through early spring. It does not currently have the capability to extrapolate intensity of grayshade associated with the cloud growth or decay implied in the differences between the two initial satellite images.

Apart from simple advection, cloud grayshade change could be the result of thickening/thinning, vertical ascent, or horizontal spreading of the cloud as it either moves horizontally or remains stationary. Convection is a major problem in this regard that is most prevalent during the warm season in the midlatitudes and throughout the year in the tropics. Rapid development and dissipation of cloud often (though not always) associated with convective activity simply cannot be resolved by the cross correlation technique.

Efforts to incorporate the effects of convection in the scheme are understandable considering its effect on the distribution of cloud. However, attempting to parameterize developmental and dissipative processes in the procedure while simultaneously preserving its ability to provide forecast images fairly quickly (and with a minimum of outside data sources) is unrealistic.

The simplest approach is to calculate the difference in grayshade for each pixel from the first to the second image, and then to add that difference for each of the five forecast images. While uncomplicated, this method obviously fails when the trend established for the first two images is reversed over the next several hours. Even when this does not occur, the increment (or decrement) of grayshade determined from the two observed images can be substantial for many pixels. For example, the range of grayshades is from zero (black) to 256 (white). If a particular pixel of interest has a grayshade of 160 units in the first image and 180

in the second, the increment is 20 units. By the 5th forecast image, 100 units would be added to the grayshade for a total of 260 units. This would automatically be reset to the displayable maximum of 256, but the cumulative effect of many such pixels would be splotchy and artificial-looking "cloud" in the forecast images (the normal range of grayshades in our database images is roughly 60-170). Analogous results could occur at the other end of the scale as well. In fact, this extreme stretching of grayshades was all too common when applying this "grayshade trend" approach. There may be some promise in somehow scaling the increments/decrements so as to remain in the normal range of grayshades for satellite images, and we hope to look into this in the near future.

Our current work centers on inferring (rather than modeling) development and dissipation of cloud using cloud climatologies, a strategy most likely to be successful in areas where cloud cover has a strong diurnal signal (such as the tropics). Two potential methods for correcting the advected grayshade value for diurnally-associated growth or decay were considered in this work unit. The first can be thought of as a climatological blending approach. It involves modifying standard cross correlation forecasts of pixel grayshade intensities on the basis of hourly cloud climatologies. The other uses harmonic analysis to discern a signal in the temporal variation of grayshade over time at a given location or region. The diagnosed signal can then be used to nudge the standard cross correlation forecasts of grayshade intensities. Both methods, described in detail below, depend on the availability of an hourly cloud analysis archive. Hourly fractional cloud cover, as determined by the SERCAA cloud analysis algorithms, is archived on a (25 km resolution) grid basis.

2.4.1 CLIMATOLOGICAL BLENDING

The first step in using this method is to compute the hourly-averaged grayshade value over a sample period (in our case, ten days) for each 1/16th mesh location (where the 1/16th mesh grayshade value is, in turn, the average of the grayshades of all pixels in that 1/16th mesh box). Then, denoting the hourly-averaged grayshade value $\{x(I,J,N)\}$, where I,J are the indices of the 1/16th mesh grid box that a given downstream pixel lies in, and N is the hour index (N=1-24 corresponds to UTC=00-23), the assigned grayshade value for the downstream point is given by

$$X_{i,j,n} = Xi'_{i',j',n-1} + (\{X\}_{I,J,n} - \{X\}_{I,J,n-1}) \quad (1)$$

where n = UTC hour index of the forecast time
 i, j = Cartesian indices of the downstream pixel location
 i', j' = Cartesian indices of the upstream location

This formulation assumes that an iterative approach is used in the cross correlation technique; that is, the grayshade distribution for the nowcast image is always derived from the previous hour's image. If the non-iterative approach is being used, as we recommend, $n-1$ in (1) above should be replaced with n_0 , signifying the hour index corresponding to the initial time ($t=0$, the second satellite image time) of the nowcast.

Application of climatological blending to the Eastern Mediterranean and Eastern Asia ROIs produced less than satisfactory results. The increment of grayshade added to or subtracted from the forecast greyshades based on hourly grayshade climatology was generally far too small to simulate cloud growth or dissipation. While disappointing, this finding inspired an alternative technique that preserves a wider range of grayshade values by eliminating the need to use hourly average grayshade values based on many images. This has the potential to produce forecast images with more dramatic increases/decreases in brightness and areal coverage characteristic of cloud development and dissipation. This approach will be tested, and documented in a follow-up report.

2.4.2 HARMONIC ANALYSIS

Given a suitably long time series (for a given season, since the temporal variations are likely to be seasonally dependent) of grayshade values for a given point, pixel, gridpoint, or region, harmonic analysis can be used to discern the strength of the more significant components of the temporal variation. If the first several harmonics of the analysis, given by

$$X_h(t) = [X] + \sum_{i=1}^{N/2} \{A_i \sin(\frac{2\pi}{P} it) + B_i \cos(\frac{2\pi}{P} it)\} \quad (2)$$

where

- i = number of the harmonic (integer between 1 and $N/2$),
- N = number of observations in the time series
- P = fundamental period of the sample (total time period)
- $[X]$ = sample mean
- t = time index of the time series (time increment of the elements of the time series, in the same units as P)

explain a dominant portion of the total variance of the time series, then it may be possible to use a truncated version of (2) to estimate the grayshade value at a given location according to the historical record of its temporal variability. If the fraction of the explained variance is F , we might assign a grayshade value to the downstream location given by

$$X_a = (1-F) X_t + F X_h \quad (3)$$

where X_a = the assigned grayshade value at the downstream point,
 X_t = the upstream grayshade value,
 X_h = the output of the truncated harmonic analysis for the
downstream point.

In this way, the computed grayshade value is a blend of the trajected and historic grayshade values, with the proportions dictated by the fractional explained variance of the historical record. See the Appendix for the computation of the above terms.

In the harmonic analysis, the fundamental period P is the time duration of the sample (in hours) of the cloud data used to develop the method. We can determine the harmonic that corresponds to a particular period of oscillation of interest using the expression $P/i = p_i$, where p_i is the desired period. For example, in a 10-day sample of hourly data, $P = 240$. The harmonic corresponding to the diurnal signal ($p_i = 24$) would be $I = 10$. We can then compute the fraction of variance explained by the $I = 10$ harmonic (see Appendix) to determine its contribution to the variance in the time series. If we found that it was a major contribution then our harmonic truncation I would have to be greater than or equal to 10.

In the application to the hourly SERCAA pixel grayshade values, if the "locations" are chosen as entire SERCAA 1/16th mesh boxes, the grayshade values would be averaged over the 1/16th mesh boxes first, and the time series would be composed of these area-averaged values. Then the truncated time series would be computed as described in the previous paragraph for each 1/16th mesh box, and the equation for that box is applied to any downstream pixel located in that box.

Limited testing of harmonic analysis on images in one ROI has produced inconclusive results to date. As with the climate blending approach described above, the technique's dependence on cloud climatologies and inherent averaging of grayshade values may result in a failure to produce realistic changes in the appearance of cloud over time that is characteristic of cloud growth and dissipation.

3. DEVELOPMENT OF A GRAPHIC USER INTERFACE FOR THE CROSS CORRELATION TECHNIQUE

It has become apparent that any hopes of eventually making the cross correlation technique an operational tool for weather forecasters (our ultimate goal) depend just as heavily on the development of a user-friendly graphic user interface (GUI) as on generating more realistic forecast images by improving the technique itself. The developmental interface that currently exists is adequate for

research purposes, but would almost certainly discourage a forecaster from using the tool in an operational setting. We have therefore enlisted the services and resources available at the Computer Science and the Psychology Departments at the University of Massachusetts at Lowell (UML) to lend image processing, computer display and human factors experts to the cross correlation effort. Working in close cooperation with PL/GPA personnel, the UML experts will produce an operationally enhanced version of the cross correlation cloud forecast system. This will require three main components of work, expanded upon below: (1) port the system to C and UNIX-based workstations and optimize the code for speed; (2) develop a window-based user interface in the X-windows/Motif environment; and (3) create workstation-accessible documentation, help and a tutorial to support user familiarization and training.

3.1 Porting and Code Optimization

The trend in scientific and engineering computing is towards UNIX-based workstations, with the majority of programs now being developed in C (or sometimes C++). Thus it is advisable to port the system to C from the current FORTRAN version. This, along with code optimization, has in fact already been accomplished through the UML contract and resulted in faster run times. Moreover, advanced workstations will provide much faster processing, estimated at up to an order of magnitude greater than the current VaxStation/VMS environment. This improved performance can be used to accomplish greater speeds using the current (384 x 384) images, or to trade off some of that speed to handle larger images (up to 1280 x 1024). It can also be assumed that advanced workstations will be deployed in increasing numbers in the field, thus enhancing the availability and utility of this system in the various intended field settings.

3.2 Development of a User-Friendly Interface

The primary concern is to make the system as user-friendly as possible. The current system provides a rather primitive command-line interface. While adequate for research and development, operational forecasters would experience difficulties working with it. The aim is to take full advantage of the multiple window capabilities of advanced workstations; specifically, to develop the interface in an X-windows/Motif environment with point-and-click buttons/menus. The design of the interface will take place in parallel with the porting of the current system into Unix/C. Additional features intended to make operation of the system as easy as possible include full date/time labeling of each displayed image, forward and backward animation capability at a user-determined speed, display of latitude and longitude of any point within an image via mouse click. When executed in a non-realtime mode (delayed until verification images are available), "on the fly" verification of forecast images will be available as well as graphical display of areas of over-and under-forecasting on a pixel by pixel basis.

3.3 Development of Documentation, Help, and Tutorial

The remaining concern in operational enhancement is to provide the user with help in understanding the basic process and in learning how to use and interpret the cross correlation technique. This requirement will be met by creating on-line written documentation explaining how to run the system, and through a tutorial designed to take the operator step by step through the process.

4. CONCLUDING REMARKS

Development and enhancement of the cross correlation technique by PL/GPA is a direct response to a documented Air Force need for accurate short-range forecasts of cloud distribution. An added requirement is the ability to successfully use the technique in data-restricted tactical environments. Initial study showed that the cross correlation technique demonstrated significant promise. Based only on two consecutive geostationary satellite images over a given location, the technique not only met the latter requirement, but was superior to several techniques that track and forecast only individual cloud features.

While endorsing cross correlation as a viable image forecasting technique, the initial study also identified several problems/deficiencies that required further research. These included terrain advection, distortion at image borders, loss of visual contrast over time, and inability to forecast cloud development and dissipation. All but the last issue have been successfully addressed in the current study. Efforts continue to infer realistic cloud development and dissipation while simultaneously retaining the efficiency and simplicity of the current version of the technique.

Finally, with an eye toward potential operational implementation of the technique, work is currently being done under contract to port the entire cross correlation code to the UNIX platform to maximize portability and to produce a user-friendly GUI. We expect that this effort will facilitate inclusion of the technique as one more tool for forecasters to use in predicting the weather.

Table 1. Comparison of Mean RMSE and Standard Deviations for Eight Cross Correlation Cases With and Without Bilinear Interpolation, Using Observed Satellite Imagery at 30 and 60 minute Intervals. RMSE and standard deviations are expressed in grayshade units.

| 30 Minute Interval | | | | | |
|--------------------------|-------|-------|-----------------------|-------|-------|
| Without Bilinear Interp. | | | With Bilinear Interp. | | |
| Fcst Interval | RMSE | S. D. | Fcst Interval | RMSE | S. D. |
| 0.5 h | 8.69 | 1.75 | 0.5 h | 8.30 | 1.66 |
| 1.0 h | 12.67 | 2.46 | 1.0 h | 11.66 | 2.28 |
| 1.5 h | 14.98 | 2.86 | 1.5 h | 13.62 | 2.76 |
| 2.0 h | 16.65 | 3.81 | 2.0 h | 15.54 | 3.35 |
| 2.5 h | 18.34 | 3.87 | 2.5 h | 16.09 | 3.85 |

| 60 Minute Interval | | | | | |
|--------------------------|-------|-------|-----------------------|-------|-------|
| Without Bilinear Interp. | | | With Bilinear Interp. | | |
| Fcst Interval | RMSE | S. D. | Fcst Interval | RMSE | S. D. |
| 1.0 h | 13.14 | 2.68 | 1.0 h | 12.08 | 2.50 |
| 2.0 h | 17.63 | 3.64 | 2.0 h | 15.81 | 3.76 |
| 3.0 h | 20.43 | 4.59 | 3.0 h | 18.19 | 4.90 |
| 4.0 h | 22.02 | 5.41 | 4.0 h | 19.14 | 5.89 |
| 5.0 h | 23.97 | 6.27 | 5.0 h | 20.11 | 6.56 |

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Appendix

Harmonic Analysis Method

The time series of N data values can be expanded into a Fourier Series in the form:

$$X(t) = \bar{X} + \sum_{i=1}^{N/2} [A_i \sin(\frac{2\pi}{P}it) + B_i \cos(\frac{2\pi}{P}it)]$$

where

X is the estimated value of the variable whose time series is being analyzed;

t is the elapsed time in the time series (in the same units as P)

$\bar{X} = \frac{1}{N} \sum_{j=1}^N x_j$, the sample mean of the sample values x_j ;

P the fundamental period, (equal to the total temporal period of the sample);

i is the harmonic index - there are $\frac{N}{2}$ harmonics in a data sample of N ;

$$A_i = \frac{2}{N} \sum_{j=1}^N [x_j \sin(\frac{2\pi}{P} i t_j)],$$

$$B_i = \frac{2}{N} \sum_{j=1}^N [x_j \cos(\frac{2\pi}{P} i t_j)],$$

except

$$A_{N/2} = 0, B_{N/2} = \frac{1}{N} \sum_{j=1}^N [x_j \cos(\frac{2\pi}{P} \frac{N}{2} t_j)]$$

Then the fraction of explained variance by each harmonic is given by

$$F_i = (1/2)(A_i^2 + B_i^2) / S_x^2$$

where $S_x^2 = (1/N) \sum_{j=1}^n (x_j - \bar{X})^2$, the sample's standard deviation

Finally, the fraction of explained variance over I harmonics is given by

$$F_I = \sum_{i=1}^I F_i, \text{ so that } F_{N/2} = \sum_{i=1}^{N/2} F_i = 1.0$$

Usually, $I \ll N/2$, since most of the explained variance should be in the first several harmonics. If not, it is an irregular oscillation.